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Linking Biological Models and Spatial Descriptions of Environmental Complexity with Coupled Models

INTRODUCTION: Effective planning and management of water resources require models to predict and evaluate the multiple biological, economic, physical, and social impacts that may result from any proposed hydraulic infrastructure design plan or operating policy. Different stakeholders care about different sets of these impacts. Models allow planners to identify the tradeoffs among the values of various conflicting objectives that are of interest to the stakeholders. Models can also aid in the synthesis of alternative designs, plans, or policies that may help reduce conflicts among the interested stakeholders. Those who develop and use models to assist in the solution of planning and management issues and problems must work with specialists from multiple disciplines. These multiple impact prediction models must be developed and calibrated based on knowledge that comes from these different disciplines.

Coupling water resource management and aquatic ecosystem management, the subject of this paper, involves both engineering and biology, among other disciplines. The literature cites many engineering and biological models designed to predict the impact of alternative water management policies and practices on aquatic species. They are fundamentally different. This is due in part to the fact that they commonly focus on different parts of aquatic ecosystems. Typical biological processes of interest to engineers have been those that govern what happens to organisms at lower trophic levels (e.g., bacteria, algae, and protozoa), such as nutrient regeneration, microbial respiration, and photosynthesis (Chapra 1997, Schnoor 1996, Thomann and Mueller 1987). Increasingly, engineers involved in river management and restoration are having to consider higher trophic level organisms, e.g. the management of salmon habitats in regulated river systems such as the Columbia River in North America or the Rhine River in Europe. Higher trophic level processes have been studied and modeled, usually by biologists (Berggren and Filardo 1993; LePage and Cury 1997; Nedorezov and Nedorezova 1995; Sekine, Imai, and Ukita 1997; Tischendorf 1997; Zabel 1996). This difference in scale of focus has resulted in the development of different modeling approaches by the two disciplines. The goals of this technical note are to describe, in general terms, the contrasting models used by biologists and engineers and to show how these models can be combined into a single coupled framework. The coupled framework uses the strength of engineering water quality models to predict spatial and temporal patterns in water quality with the power of biological models to predict population dynamics. Once identified, the coupled model framework builds on the strengths while reducing the weaknesses of each of the two separate modeling paradigms. The coupled model provides a tool for integrating water resources and aquatic ecosystem planning and management.

To understand how the tools and approaches of biologists and engineers differ, it is first useful to review how ecosystems are structured. Ecologists often view ecosystems as being organized into different hierarchical levels that function at different temporal and spatial scales. Each subsequent hierarchical level is comprised of preceding simpler levels, the processes that define behavior at these simpler levels, and their suite of interactions with higher levels. For example, the dynamics of individual populations can be considered as the components of community dynamics. Community level dynamics integrate interactions between different populations, interactions not completely depicted at population-level dynamics. Therefore, descriptions of population dynamics from a community level may differ from descriptions of population dynamics at a population level since additional processes are included as hierarchical levels increase. As eloquently summarized by Odum (1971), "An ecosystem is more than the sum of its parts."

Scale can be considered as a surrogate for hierarchical levels of organization since different hierarchical levels can be partially described by their temporal and spatial scales. A process like the movement of molecules, i.e., Fickian diffusion, has a small spatial scale and short temporal scale as opposed to the movement of large organisms, such as blue whales, that may move on planetary spatial scales and temporal scales of decades (Figure 1). A comprehensive description of an ecosystem sufficient to manage and plan water resources at a comprehensive ecosystem level must include processes that span wide ranges in scale.

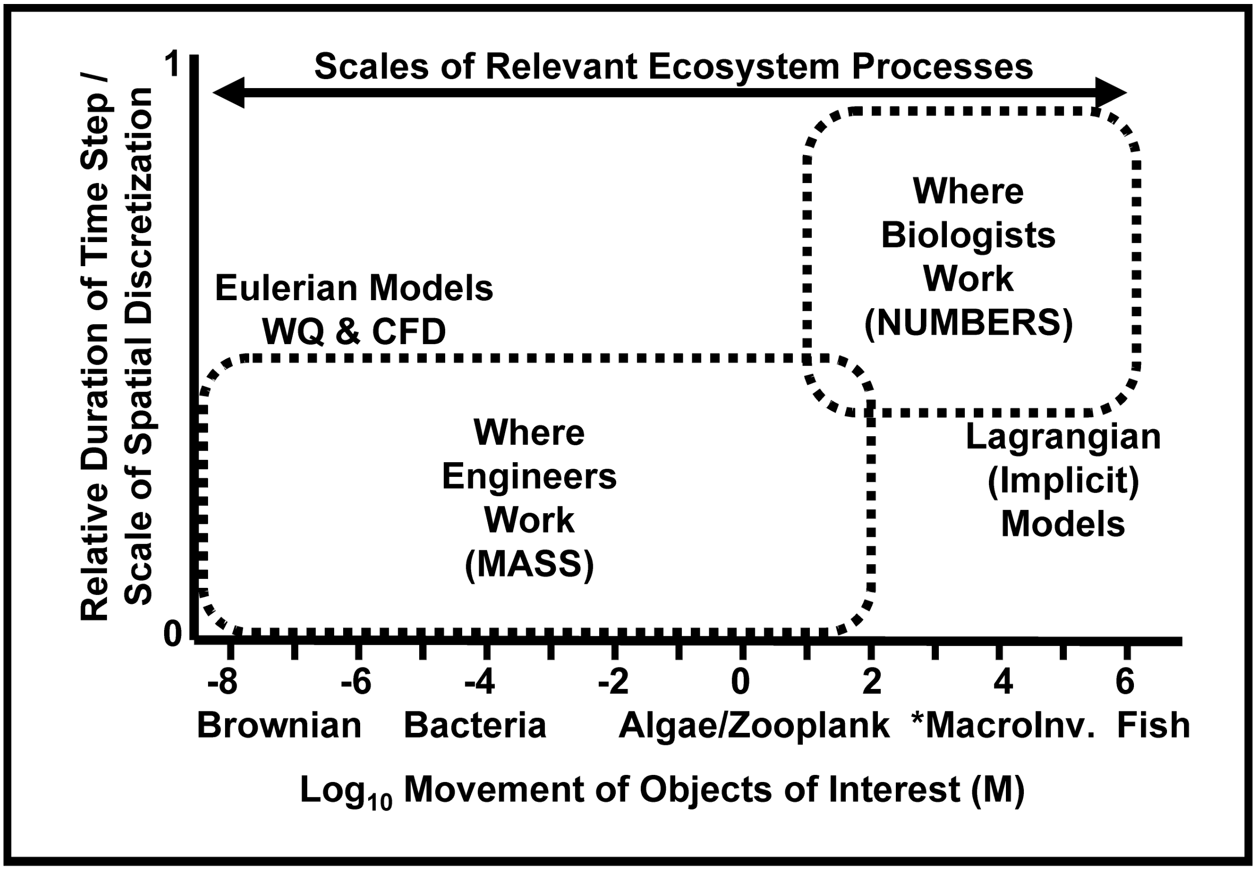

Figure 1. Ordination of common tools used by biologists and engineers along a relative temporal scale and spatial scale by scale of movement (MacroInv=macroinvertebrates)

WATER RESOURCES ENGINEERING MODELS: Water resources engineering is a wide and diverse field employing many useful modeling approaches. For example, numerical hydraulic and water quality models based on computational fluid dynamics are commonly employed in water resources engineering to address an array of issues including structural design, operation, impact prediction, and restoration planning. Most of these models use a Eulerian framework to discretize the physical domain into a grid of interconnected cells. Eulerian models typically employ a series of assumptions:

- Processes of interest can be averaged within cells without significant loss of accuracy.
- Particles and processes are uniformly dispersed within cells.
- Individual particles lose their separate identities within cells.
- A grid-specific origin is used to implement conservation of mass and momentum concepts.
- Space within the physical domain of interest represented by the grid is organized into 3-dimensional Cartesian representation using x, y, and z axes.

The Eulerian framework appears to work best when the process being simulated integrates over small spatial scales and short temporal scales so that the error produced by successively averaging processes within and between cells is small (Figure 2). These processes and the constituents they produce and transform can then be advected, dispersed, and transformed within the grid representation of the physical domain.

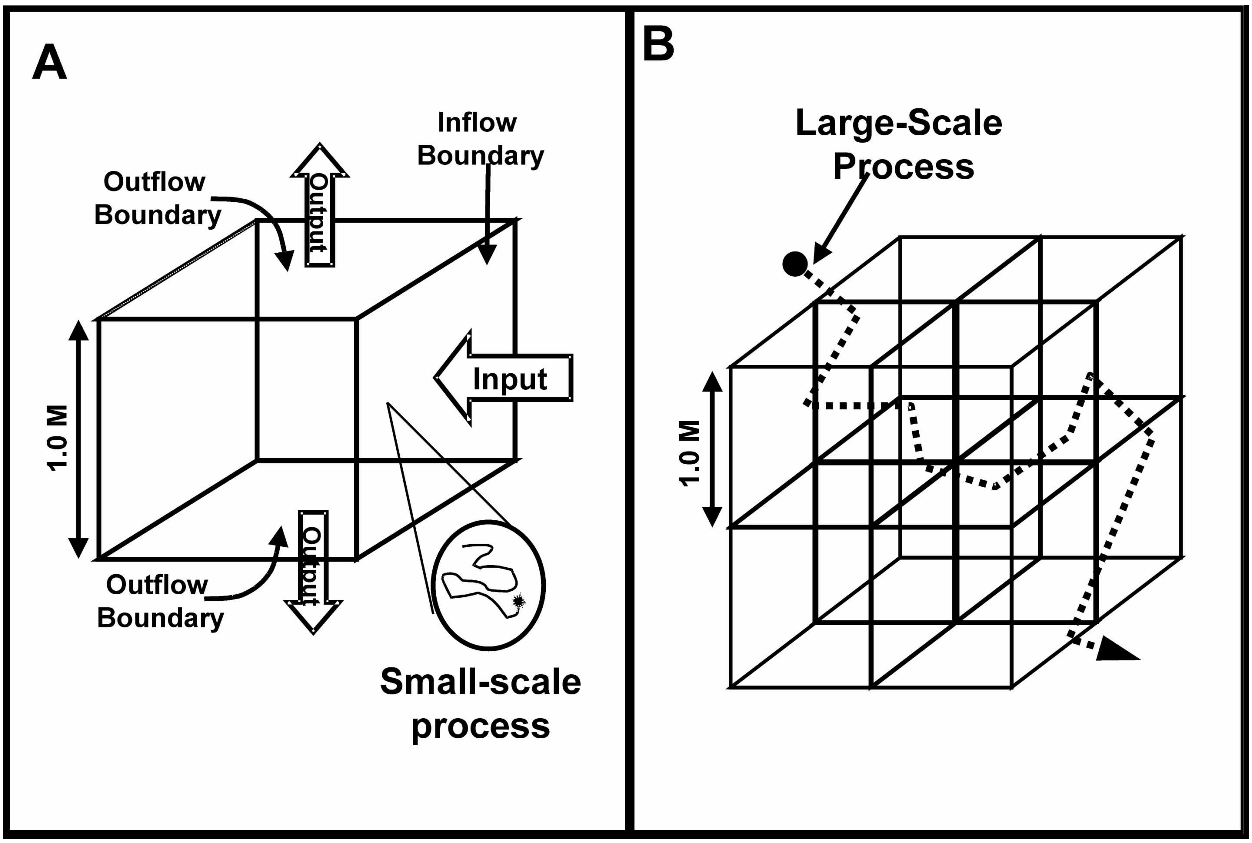

Figure 2. Comparison of the relationship between scale of discretization and scale of process movement for a small-scale process, such as Fickian diffusion (A) and a larger scale process such as fish swimming (B). The grid shown in (B) is for scale reference only and is not part of the Lagrangian reference framework

BIOLOGICAL MODELS USED IN WATER RESOURCES PLANNING: Biologists use a number of different population models for water resources planning and management. Population models predict the change in population size over time. These models are often applied to address aquatic environmental issues involving members of higher trophic level populations (such as fish) and mobile macroinvertebrates (such as shrimp and crabs). Close inspection of the movement patterns of such individuals within the population being simulated typically shows that the movement for certain key life stages or age stages is considerably larger than the scale that would typically be used to discretize the physicochemical environment (Figure 2). As a consequence of their large-scale movement behavior, they systematically violate the assumptions, listed on the previous page, necessary to describe their dynamics in a Eulerian framework:

- Individuals of a highly mobile aquatic species cannot be averaged within cells because their movement patterns cut across multiple cells within one time-step and because their range of movement in a single time-step significantly exceeds water velocities associated with advection and dispersion. Therefore, their movement cannot be simulated using only advection and dispersion algorithms.
- Similarly, individuals cannot be uniformly dispersed within cells and lose their individual identity without significant loss of accuracy. The movement dynamics of individual organisms change with sex, size, age, stage, physiological condition, and with light and other environmental variables. Therefore, their separate identities must be preserved as they move through the modeled domain to prevent accumulation of errors.
- The grid-specific global origin and vector depiction of flow fields common to Eulerian frameworks (necessary to implement conservation of mass and momentum) are inadequate to describe the spatial orientation of most large mobile biota. Large, actively swimming organisms orient to streamlines or to other features of the immediate environment. That is, fish orient to the flow resultant and not the flow vectors and they utilize a local origin, perhaps their own location, or an immediate feature and not the global origin of a Eulerian system.

Models used by biologists acknowledge the physicochemical environment in several ways. Most commonly, biological models simply ignore physicochemical patterns of the environment and how large aquatic biota may respond to this environment and treat the omission as an assumption of the model. That is, simple population models are implicitly Lagrangian in that they acknowledge the importance of environmental heterogeneity as an assumption. More recently, population modelers have developed meta-population models in which a population is spatially distributed into several subpopulations that interact via immigration and emigration. Most recently, individual-based population models (IBMs) simulate individuals or groups of individuals in ecosystems (LePage and Cury 1997). IBMs incorporate physicochemical information from models or measurements into their models; however, these models are still primarily population models and have not rigorously and systematically incorporated the power of Eulerian hydraulic and water quality models into a larger framework. Although progress is made, the goal of realistic simulation of ecosystem processes across a broad range of scales remains elusive.

THE SOLUTION IS TO COUPLE: The key to developing ecosystem-modeling capability across a broad range of scales is to combine the two separate modeling frameworks into a single, unified framework termed the Coupled Eulerian-Lagrangian Hybrid (CEL Hybrid) Ecological Modeling System. The Couple, a generic linking program built on particle tracking concepts, is the unique information transformation/translation module of CEL Hybrid models that allows the analysis to switch between the two reference frameworks without information loss. Particle tracking algorithms emulate the path made by a neutrally buoyant particle passively transported through a physical domain represented as a grid. It takes discontinuous information and allows one to interpolate to intermediate points of interest to generate a nearly continuous pathway through a system at specific points of interest instead of at arbitrary points in a grid corresponding to the cell structure of the Eulerian reference frame (Martin and McCutcheon 1999). Particle tracking logic enables a modeler to use the strength of a Lagrangian framework to maintain the integrity of individuals as they move through simulated space while concurrently using the power of the Eulerian framework to simulate the physico-chemical environment and other characteristics of the system over time and space. The Couple has the following functions and subroutines as it transforms and translates information between the Lagrangian and Eulerian reference frames:

- An embedded IBM simulates the population dynamics of the target species.
- The age, mass, composition, exposure history, accumulated distance moved, sex, cell residency, and other relevant information about each particle that can be used to summarize information about the target species from a uniquely Lagrangian reference frame are recorded and updated.
- During the Lagrangian phase of the coupled simulation, a subroutine called the Numerical Fish Surrogate (NFS) simulates the movement behavior of individuals or groups of individuals for the target species.
- After population adjustment by the IBM and redistribution of individuals by the NFS, the Couple summarizes the distribution of individual particles by their cell location and then computes their total biomass or other information that is needed for the Eulerian part of the hybrid modeling system.
- The Eulerian module of the modeling system uses the transformed and translated information provided by the Couple to update water quality and to feed back information that can be used to simulate bioenergetics within the IBM, if appropriate.
- The Couple reconstitutes the individual particles from the Eulerian grid and adjusts their individual sizes and other characteristics based on bioenergetics information fed back from the Eulerian module.

EXAMPLE APPLICATION: The most unique aspect of the Couple is the NFS, because most of the subroutines that perform other functions of the Couple already exist as separate, unconnected elements. The NFS is a particle-tracking algorithm enhanced with behavioral rules that translates the sensory inputs to biological individuals, either Eulerian-based quantities (e.g., temperature) or Lagrangian-based quantities (e.g., distance to nearest-neighbor), into emergent Lagrangian-based movement behavior. NFS development consists of a series of integrated steps, including: (a) obtaining suitable field data for quantitatively describing the movement of the target fish species, (b) obtaining a calibrated and verified hydrodynamic and water quality model, (c) integrating a particle-tracking algorithm into the hydrodynamic and water quality model, (d) developing stimuli-response rules for the water quality regimes along with the movement of virtual fish, and (e) presenting model results in a format consistent in scale and resolution to the field data obtained in step (a).

Applying NFS to simulate the movement of blueback herring, *Alosa aestevalus,* in J. Strom Thurmond Lake in the state of Georgia is described as an example of how a CEL Hybrid model can be used to couple the movement behavior of a fish using a Lagrangian framework to simulated water

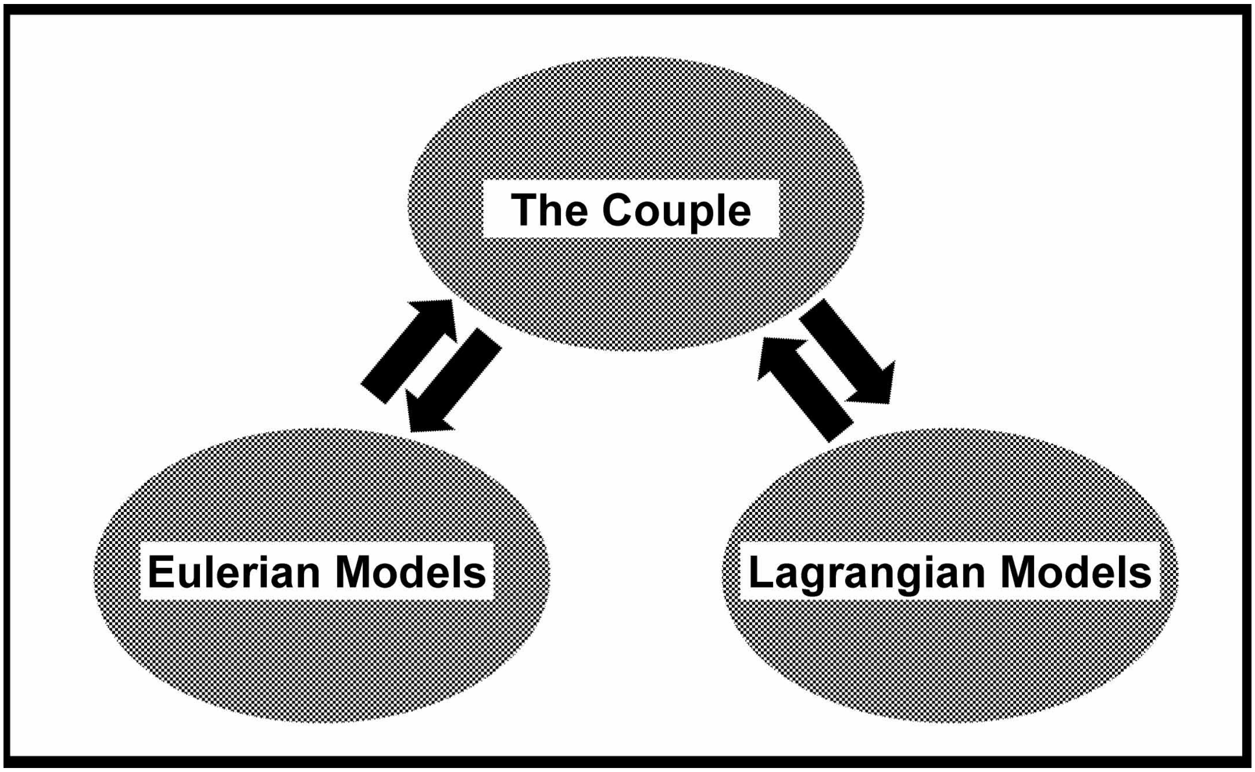

Figure 3. The two contrasting reference frameworks used in modeling are coupled together by a linking program that translates and transforms information as it is passed from one modeling framework to the other

quality conditions in a reservoir. Calibration and verification of the water quality model are described in Cole and Tillman (1996).

The NFS considers that each simulated fish is surrounded by a sensory ovoid that represents the outer boundary of a volume within which a fish could search to determine the strength of gradients of different parameters (Figure 4). If necessary, the ovoid can be distorted to match the axis distortion of the grid. The gradient information is then evaluated by swim path selection rules. The virtual fish then swims through the physicochemical environment simulated by the Eulerian module of the CEL hybrid model. Its swimming speed can also be adjusted by ambient dissolved oxygen concentration or water temperature.

NFS performance can be determined using standard model calibration methods. For this analysis, the distribution of virtual fish in the modeled system was calibrated to fish distribution data collected over a several-week period in August of 1996. The three-dimensional distribution of fish in the size range of adult blueback herring was obtained using mobile hydroacoustics together with gill nets to identify what proportion of the acoustic targets in the appropriate size range was blueback herring. The observed distribution of blueback herring in J. Strom Thurmond Lake was collapsed vertically and horizontally (Figure 5) and to within the nearest hour before being compared to the distribution of similarly collapsed virtual fish in the modeled system.

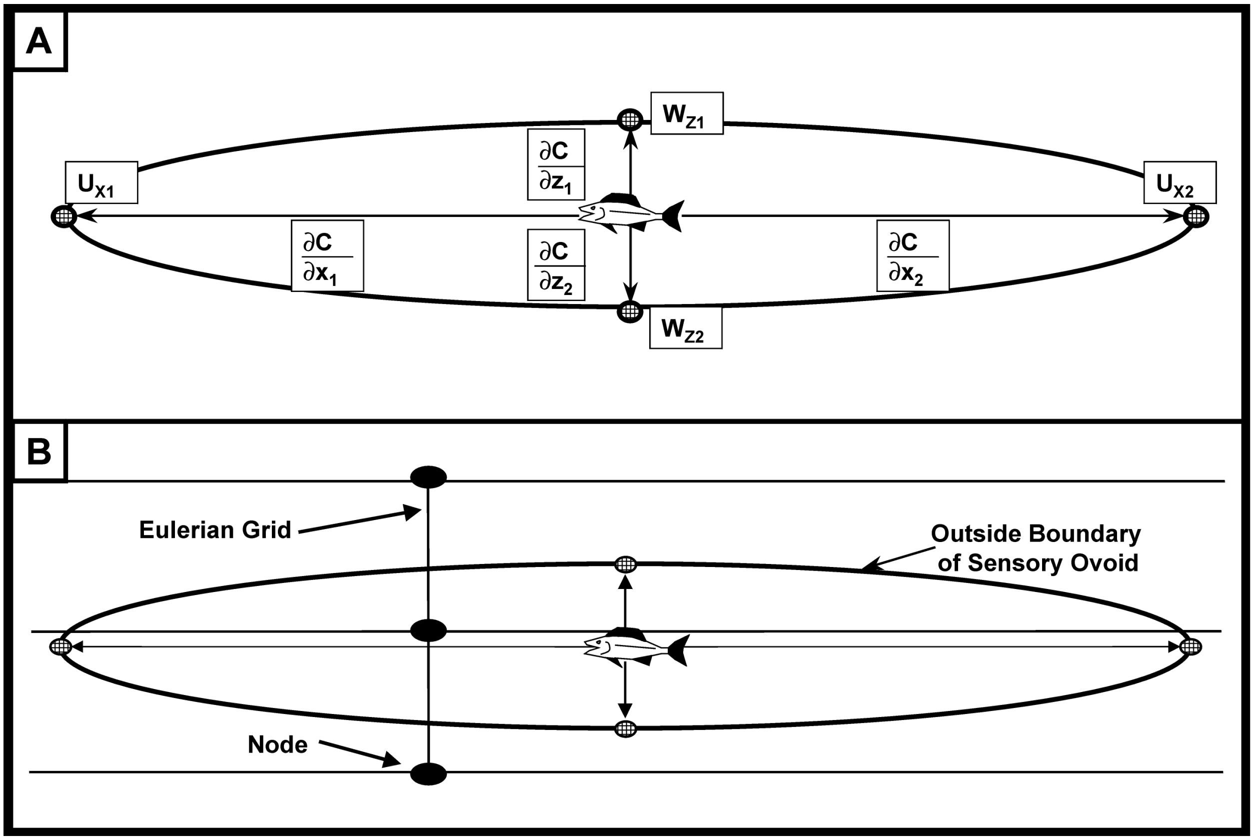

Figure 4. (A): Representing the search volume of a fish as an ovoid shape. The outside boundary of the sensory ovoid is determined as the (maximum fish sustained swimming speed) x (time-step). For each time-step, the magnitude of movement in each direction is obtained from a random distribution with a mean of zero and a maximum value represented by the outside ovoid boundary. (B): The movements in each direction allow the virtual fish to obtain gradient information about C where C=Horizontal Velocity (U), Vertical Velocity (W), Temperature (T), and Dissolved Oxygen (DO). Information necessary to determine gradients is obtained by interpolation from the Eulerian module.

Calibration results from the simulation show that the regression coefficients observed for blueback herring distribution and coefficients predicted by the CEL hybrid model matched, with an r^2 of 0.93 for vertical distribution and an r^2 of 0.67 for longitudinal distribution.

DISCUSSION: A CEL hybrid model can be employed to simulate the movement of fish in complex, dynamic environments over time and space scales that are realistic for water resources issues. The authors know of no other model applications that use either exclusively a Eulerian reference frame or exclusively a Lagrangian reference frame in which predictions of movement behavior can be made with the accuracy and resolution of the coupled CEL hybrid model presented in this paper. In this case, a biologist (the senior author) developed the equation used to describe the behavior of blueback herring, an engineer (A. Goodwin) developed the Eulerian water quality model, and engineers and biologists developed the Couple collaboratively.

SUMMARY: Estimating ecosystem impacts from alternative water management policies or practices involves an understanding of both engineering and biology, among other disciplines. However, the modeling approaches used by biologists and engineers to estimate these impacts are

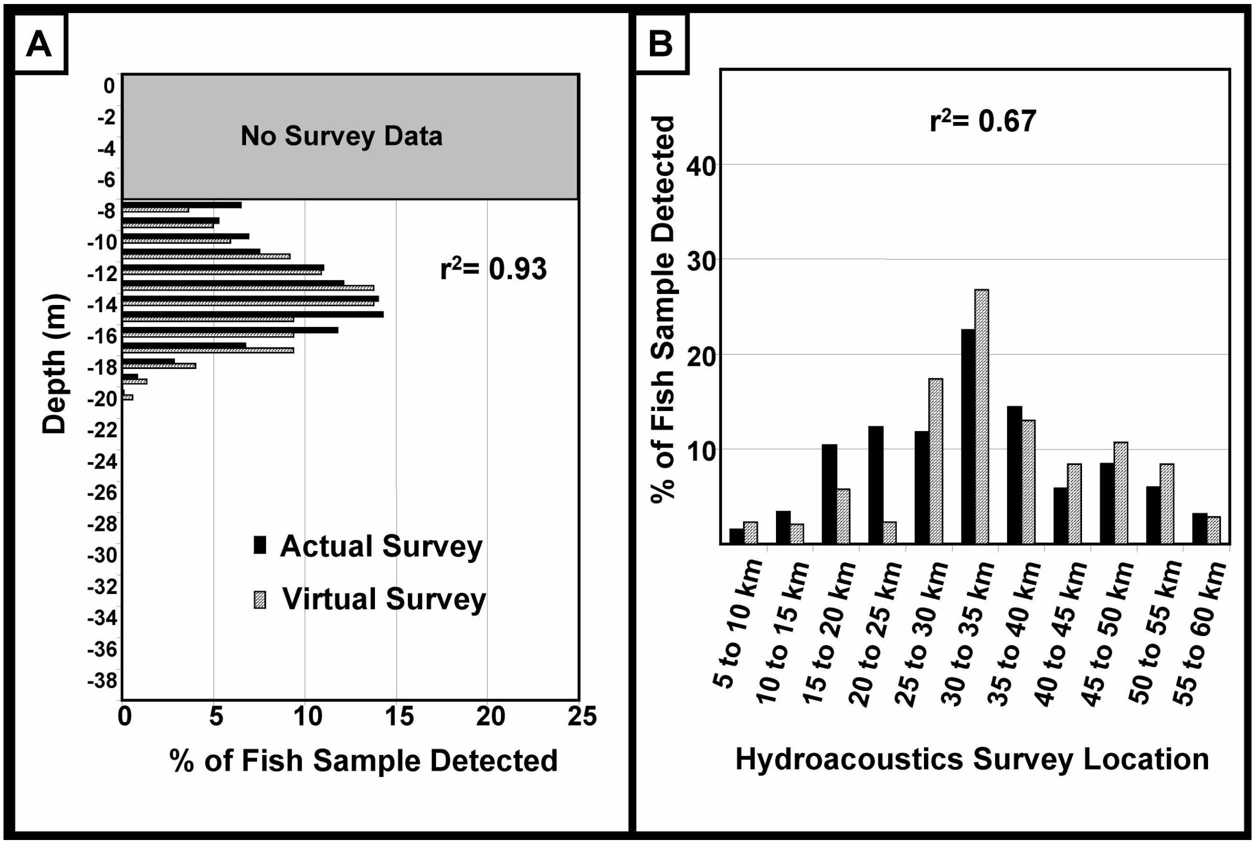

Figure 5. Comparison of predicted versus observed fish distributions from field surveys and CEL hybrid model predictions for (A) vertical and (B) horizontal distributions

usually quite different. Engineers commonly use the Eulerian modeling framework to simulate bulk water flow and the biological, chemical, and physical processes that affect lower trophic levels of ecosystems, such as bacteria, algae, and protozoa. In contrast, biologists typically use an implicit Lagrangian modeling framework to simulate population dynamics or the influences of competitors, predators, and resource availability on populations of higher trophic levels, such as fish. These two modeling frameworks can be joined together into a comprehensive coupled Eulerian-Lagrangian hybrid (CEL Hybrid) model to predict the interactions within, and the effects of water resources activities on, a wider range of ecosystem trophic levels than can either framework by itself. CEL Hybrid models use stimuli-response rules to transform neutrally buoyant objects into ‘smart’ objects, or virtual organisms, emulating the movement behavior of individuals of an aquatic species in a simulated hydraulic and/or water quality environment. Standard calibration techniques are used to achieve movement behaviors in the virtual organisms that best emulate the movements of observed species. Once the movement behaviors of a higher trophic species are incorporated within a CEL Hybrid model, the model can be used to estimate the impacts of any water resources management activity on species population processes at any one of a number of trophic levels and spatial and temporal scales.

CONCLUSIONS: The CEL Hybrid modeling approach begins by implementing the hydraulic and water quality simulation models of a natural condition for which multiple determinations of position of individuals of a target species are available. Integration of the hydraulic and biological data allows the movement of the aquatic species to be separated into passive transport and volitional swimming. Volitional swimming is then treated as a dependent variable and analyzed against hydraulic and water quality variables to develop relationships that explain movement behavior. The stimuli-response rules can be refined using information on the ecology of the species to ensure that physiological limitations or behavioral characteristics are included.

Thus, CEL hybrid models provide an opportunity to simulate complex dynamic ecosystem processes across a range of scales. However, to fully implement a CEL hybrid model requires a broad range of expertise exceeding that which is normally found in either an Engineering Department or a Biology/Ecology Department. Implementation of CEL hybrid modeling concepts, and successful ecosystem simulation, truly require collaboration between biologists and engineers.

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